

Plasticity and Metastability of AISI 204 Cu Austenitic Stainless Steel Sheets in Tension

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Abstract

A utensil grade metastable austenitic stainless steel, AISI 204 Cu was tested for plastic flow, tensile properties and strain-induced phase change, and martensite formed. Results were compared with AISI 304, a typical stainless steel usually used in similar applications. AISI 204 Cu showed higher strength properties and little lower ductility properties. Two different martensite phases, ϵ -martensite (hexagonal close-packed, h.c.p.) and α' -martensite (body-centered cubic, b.c.c) have been observed. X-ray and TEM proved the phase change.

Keyword: Martensite, Stainless Steel, XRD, TEM, UTS

INTRODUCTION

AISI 204 Cu, the low-nickel metastable austenitic stainless steels (Cr-Mn-Ni-N stainless steels), like other AISI 200 series stainless steels are a modification of the popular austenitic stainless steel grade AISI304. These metastable steels undergo strain-induced martensitic transformation during room-temperature deformation. Austenite is transformed into martensite and this affects the mechanical properties. The strain-induced martensitic transformation can occur between M_s and a much higher temperature M_d , when a certain level of plastic strain is exceeded. Two different martensite phases, ϵ -martensite (hexagonal close-packed, h.c.p.) and α' -martensite (body-centered cubic, b.c.c) have been observed. Nucleation of ϵ -martensite (h.c.p.) occurs at stacking faults. Nucleation of α' -martensite (b.c.c.) occurs at shear band intersections. The operative shear band intersections can be in the form of ϵ -martensite, annealing twins or dense stacking fault bundles [1–4, 6, 7]. Strain-induced martensitic transformation under tensile loading causes an increase in both strength and ductility. In low cycle fatigue, however, the ductility depends on

the strain amplitude. In this study, the uniaxial tensile strain-induced martensitic transformation in AISI 204 Cu is reported and a comparison is also made with the response of an AISI 304 stainless steel sheet, used as a benchmark. At present, the production of low-Ni steels in India has exceeded 4,00,000tons per annum and this grade is mainly used in utensil manufacture without adequate technical data being available to the users. More than 1,50,000tons are sold by a well-organized sector. These steels can undergo season cracking due to large internal residual stresses introduced during deformation. Also, there exist no equivalent grades in current international market in other international specifications, such as AISI 304. So, it has become essential to assess the properties of and do research on these market-driven materials [1–6].

MATERIALS AND METHOD

The sheets were tested in the as-received condition. The grain sizes were found using the linear intercept method to be $23 \pm 5 \mu\text{m}$ and $13 \pm 4 \mu\text{m}$ in the low-nickel and the AISI 304 steels, respectively. The sheet thicknesses of the AISI 204 Cu and

AISI 304 steels were 0.70mm and 0.50mm, respectively. (Sheets of identical thickness were not available, as these were taken from production runs.) Tensile tests at a constant cross-head speed of 0.5mm/min (initial strain rate, $2.83 \times 10^{-4} \text{ s}^{-1}$) were conducted on a 250kN Schenck-Trebel electromechanical testing machine capable of computer-controlled data acquisition. ASTM E8M subsize specimens were used. The tensile properties, namely, the 0.2% yield strength (YS), the ultimate tensile strength (UTS), the uniform elongation e_u , and the total elongation e_t , were evaluated. The strain-hardening exponent n , and strength coefficient K , were obtained using the Hollomon equation $\sigma = K\epsilon^n$ from a linear regression between $\ln\sigma$ and $\ln\epsilon$, where σ is the true stress and ϵ is the true strain. The strain-rate sensitivity index m , was obtained using the changing crosshead speed method on ASTM A370 sub size specimens. A strain rate jump of 11 times was involved in the present case, i.e., changing the cross-head speed from 0.1mm/min (initial strain rate, $1.43 \times 10^{-4} \text{ s}^{-1}$) to 1.1mm/min (strain rate after the jump, $1.53 \times 10^{-3} \text{ s}^{-1}$). m was calculated from the equation $m = \ln(\sigma_2/\sigma_1)/\ln(\dot{\epsilon}_2/\dot{\epsilon}_1)$, where σ_1 and σ_2 are the flow stresses at strain rates $\dot{\epsilon}_1$ and $\dot{\epsilon}_2$, respectively. To consider the effect of anisotropy, the tests were carried out on specimens prepared with their tensile axis at 0° , 45° and 90° to the rolling direction and the average values of the different parameters were determined using the relation $X_m = (X_0 + 2X_{45} + X_{90})/4$, where the subscripts denote the angle between the tensile axis and the sheet rolling direction [1,3,5–7]. The amount of α' -martensite was determined using a Helmut Fischer ferrite scope. A Shimadzu X-ray diffractometer was used to identify the transformation products: α' and ϵ -martensites. The untested and tested specimens were examined in a Philips CM12 transmission electron microscope. The detailed experimental procedures have been given elsewhere [1,3,7].

RESULTS AND DISCUSSION

The chemical compositions of the steels are given in Table 1. In AISI 204 Cu, the austenite is stabilized by manganese and nitrogen, in addition to a smaller amount of nickel compared with AISI 304. Table 2 displays the room-temperature tensile properties of the two steel sheets. The YS of the low-Ni steel is greater by 47% than that of the AISI 304. Nitrogen increases the YS by being an interstitial solid solution strengthener as well as a stabilizer of the stronger austenite phase. YS of an austenitic stainless steel can be calculated using the following (multiple-regression-analysis-based) equation.

$$\begin{aligned} \text{YS} = & 15.5(4.4 + 23[C] + 32[N] \\ & + 1.3[Si] + 0.24[Cr] \\ & + 0.94[Mo] + 1.2[V] \\ & + 0.29[W] + 2.6[Nb] \\ & + 1.7[Ti] + 0.82[Al] \\ & + 0.16[\delta - \text{ferrite}] \\ & + 0.46d^{-1/2}) \end{aligned} \quad (1)$$

Where, all element concentrations are in weight percent and d is the grain size in millimeters. An increase in the amounts of copper and manganese increases the YS, whilst increasing the nickel content decreases it. (Equation 1, however, does not include the effects of these elements.) The calculated values of the YS of AISI 204 Cu and AISI304 were greater by 41% and 31%, respectively, than the observed values. The deviations were mainly due to the treatment of YS as a linear function of the concentration of the constituent elements rather than as a non-linear function. The UTS of AISI 204 Cu was greater by 21% than that of AISI 304 steel (Fig.1). This is traced to its stronger martensite-forming tendency which is a stronger phase than austenite [1–5]. The amounts of ferrite corresponding to a true strain of 20% were 4 in the case of AISI 204 Cu and 3 in the case of AISI 304 steel but those corresponding to 40% strain

were 24 in the case of AISI 204 Cu and 17 in the case of AISI 304 steel [1-4,6,7]. The amount of α' -martensite formed as a function of tensile true strain in AISI 204 Cu could be described as the third-degree polynomial

$$FN = 0.513 - 0.0093\epsilon + 0.00018\epsilon^2 + 0.00035\epsilon^3 \quad (2)$$

While, in AISI 304, it was describable by the second-degree polynomial

$$FN = 0.66 - 0.2558\epsilon + 0.01723\epsilon^2 \quad (3)$$

Where, FN is the amount of α' -martensite formed and ϵ is the true strain in per cent. The UTS of an austenitic stainless steel

can be calculated using the following (multiple-regression-analysis-based) equation:

$$UTS = 15.5(29 + 34[C] + 84[N] + 2.7[Si] + 0.13[Ni] + 1.2[Mo] + 3.6[Nb] + 1.9[Ti] + 2[Al] + 0.46d^{-1/2}) \quad (4)$$

Where, all element concentrations are in weight percent and d is the grain size in millimeters. Cu, Cr and Mn have no effect on the UTS. The calculated values of the UTS for AISI 204 Cu and the AISI 304 steels were greater by 19% and 26%, respectively, than the observed values [1,2,7].

Table 1: Chemical compositions of the two steels selected for comparative property analysis.

Grade	Amount (wt%)						
	C	Cr	Mn	Ni	N	O	Cu
AISI 204 Cu	0.076	14.9	9.19	1.18	0.155	0.046	1.38
AISI 304	0.061	17.8	1.57	8.47	0.015	0.129	0.045

Table 2: Room-temperature tensile properties of the two steels (initial strain rate, $2.83 \times 10^{-4} s^{-1}$).

Grade	Property in different directions	YS ^a (MPa)	UTS (MPa)	e _u (%)	e _t (%)	n ^b	K (MPa)	m ^c
AISI 204 Cu	X ₀	375	858	31	32	0.36	1627	0.016
	X ₄₅	389	891	37	38	0.52	2205	0.016
	X ₉₀	391	815	29	29	0.39	1731	0.016
	Xm ^d	386	864	34	34	0.45	1942	0.016
AISI 304	X ₀	270	734	36	37	0.49	1738	0.012
	X ₄₅	254	715	43	44	0.46	1592	0.012
	X ₉₀	271	891	37	38	0.46	1580	0.012
	Xm ^d	262	714	40	41	0.47	1626	0.012

a) 0.2% offset.

b) The n values are reported to two decimal places based on an error analysis (range of standard deviation, 0.003 ± 0.009).

c) The m values are reported to three decimal places, because the variations in this parameter were observed only in the third decimal place. The strain rates before and after the jump were $1.43 \times 10^{-4} s^{-1}$ and $1.53 \times 10^{-3} s^{-1}$, respectively.

The deviations were due to the assumption that the UTS is a linear function of the concentration of the constituent elements. Also, there is no correlation available between the amount of strain-induced

martensite formed and the UTS which was more in the case of AISI 204 Cu than for AISI 304 (Fig.1). (Efforts are at present being made to include the effect of strain-induced martensite formation on the UTS.)

The flow curves are also shown as part of Fig.1.

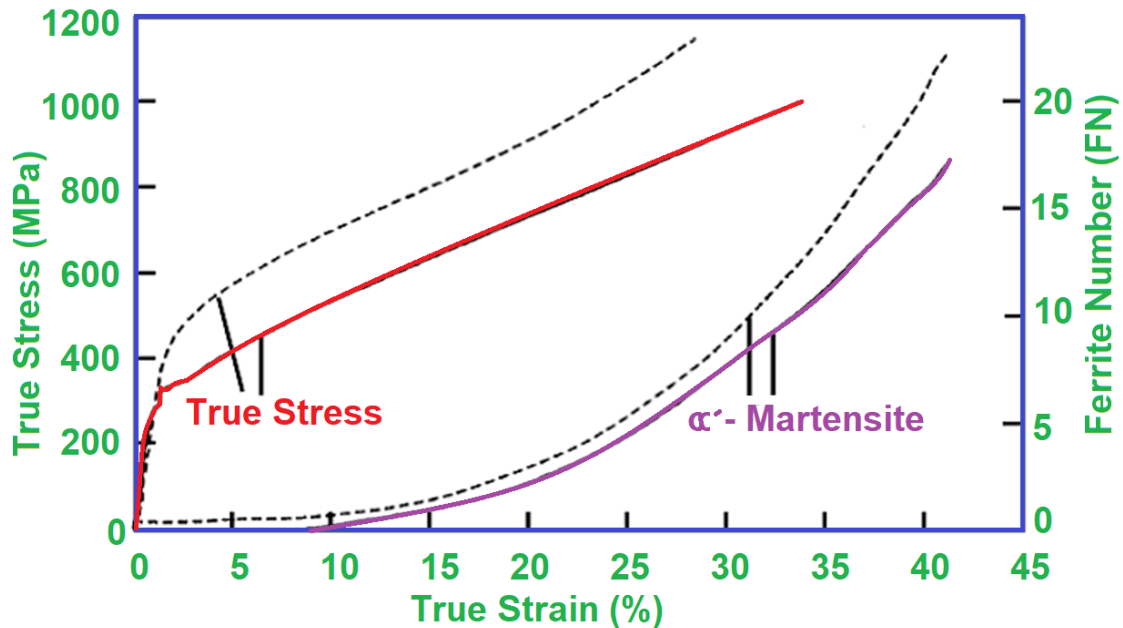


Figure 1: Flow curves and the amounts of α' -martensite formed as a function of true tensile strain in the two steels (dashed line – AISI 204 Cu, solid line - AISI 304).

The formation of strain-induced martensite during plastic flow in both cases caused an increase in the flow stress. This resulted in a high value for the ratio of UTS to YS. This ratio is 1.7 for a wide range of metals

and alloys. For a stable austenitic stainless steel this ratio is about 1.8. The values of this ratio were 2.2 and 2.7 for AISI 204 Cu and AISI 304 steels, respectively [1,2,3,7].

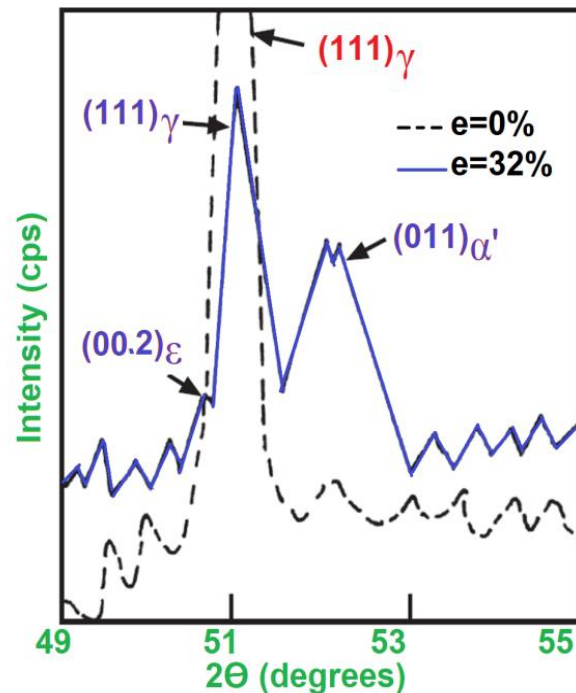


Figure 2: Phase change (martensitic transformation) in AISI 204 Cu as revealed by an X-ray analysis (Co $K\alpha$ radiation).

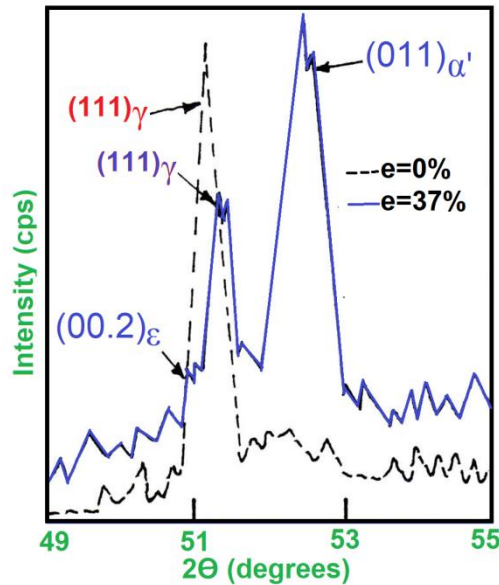


Figure 3: Phase change (martensitic transformation) in AISI 304 as revealed by an X-ray analysis (Co K α radiation).

The strain-hardening exponent was complementary to the UTS-to-YS ratio. At any particular strain, the flow stress of AISI 204 Cu was greater than that of AISI 304 steel. This was due to the presence of a higher concentration of nitrogen in AISI 204 Cu and the stronger tendency of AISI 204 Cu to form martensite (Fig.1). Different alloying elements cause changes in properties by varying amounts, and a more quantitative analysis does not appear to be possible at this stage. Strain-rate sensitivity indices were very low in both the steels and consequently post-uniform elongation was almost non-existent in AISI 204 Cu. Post-uniform elongation was 1% in AISI 304, which is also extremely small. As seen in Fig.1, in AISI 204 Cu, a larger amount of martensite formed and this increased the degree of work hardening and postponed neck formation to a greater extent. So, strain-induced martensite formation was found to be beneficial in this steel so far as ductility was concerned. However, once localized deformation started, martensite formation was not so effective in postponing fracture. Beyond a certain level, martensite formation acted as a stress raiser and the ductility decreased. That is why, the

ductility of AISI 204 Cu was less than that of AISI 304. By considering in detail the effects of a non-random distribution of second phases on ductility, it has been concluded that non-random distributions can cause significant changes in the ductility. At present, there is no analytical way available in which non-random distributions of second phases can be correlated with ductility. Figs. 2 and 3 shows the X-ray diffraction (XRD) results (a plot of intensity in counts per second versus angle 2θ , where θ is the Bragg diffraction angle) for AISI 204 Cu and AISI 304 before and after a tensile test. The steel contained only austenite (γ) before tensile deformation. So the XRD pattern displayed only one peak at around 518, but the post-deformation sample contained in addition ϵ - and α' -martensite.

A transmission electron micrograph (Fig. 4 and 5) and the corresponding selected-area diffraction pattern (inset) also established only the presence of austenite (γ). However, after deformation, two additional peaks, one corresponding to α' -martensite and the other to ϵ -martensite, appeared in the XRD pattern. The lattice parameters for ϵ -martensite were used for indexing.

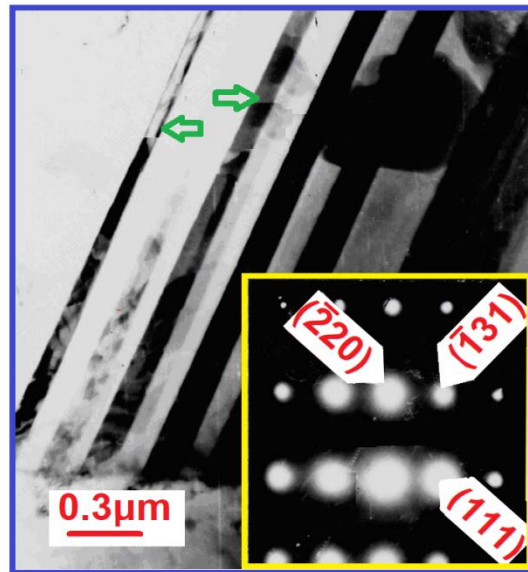


Figure 4: Bright-field TEM picture of austenite before tensile deformation in AISI 204 Cu, where twins are indicated by arrows (inset – SAD pattern of the austenite).

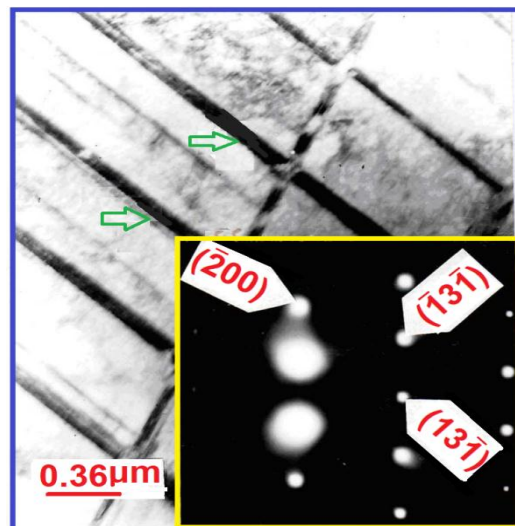


Figure 5: Bright-field TEM picture of austenite before tensile deformation in AISI 304, where twins are indicated by arrows (inset – SAD pattern of the austenite).

A transmission electron micrograph (Fig. 6 and 7) and the corresponding selected-area diffraction pattern (inset) helped to identify the presence of α' -martensite. ϵ -martensite could not be observed, perhaps owing to the high dislocation density and the presence of highly dense stacking-fault bundles. In an earlier study on AISI 304LN steel, however, the presence of ϵ -martensite within which α' -martensite was present and could be seen using transmission electron microscopy [2]. The results obtained in the present

investigation showed that AISI 204 Cu stainless steel is metastable at room temperature and undergoes a strain-induced martensitic transformation. The ratios of the UTS to 0.2% YS were 2.2 and 2.7 for AISI 204 Cu and AISI 304, respectively. In both the steels, the strengthening effect came partially from the martensitic transformation, in addition to the effects of alloying additions and work hardening. Depending on concentration, strain-induced martensite formation either enhanced or decreased the ductility.

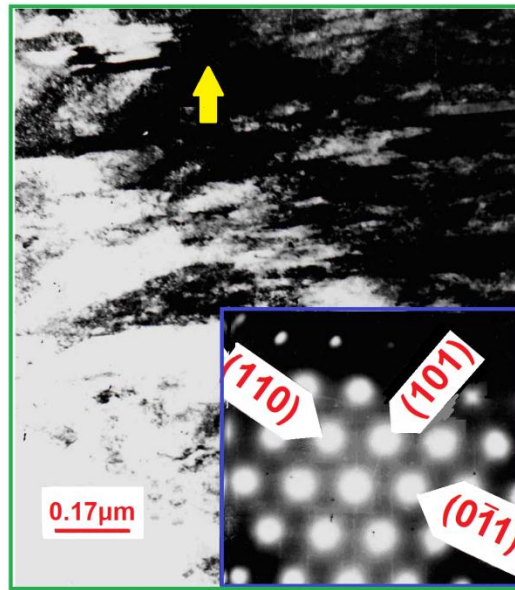


Figure 6: Bright-field TEM picture of the martensite phase after tensile deformation (true strain, 29%) in AISI 204 Cu, where α' -martensite is indicated by an arrow (inset – SAD pattern of α' -martensite).

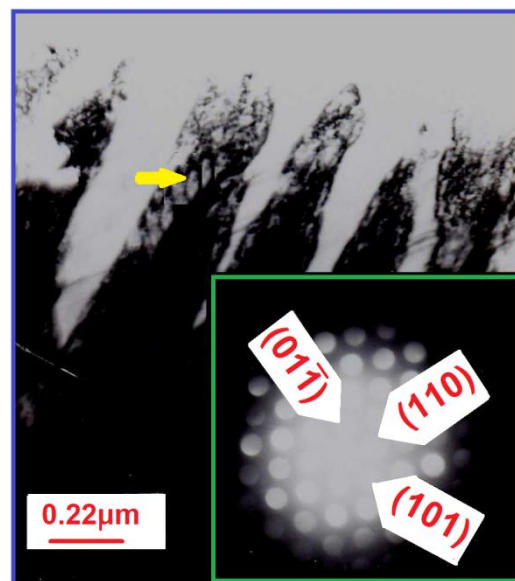


Figure 7: Bright-field TEM picture of the martensite phase after tensile deformation (true strain, 29%) in AISI 304, where α' -martensite is indicated by an arrow (inset – SAD pattern of α' -martensite).

CONCLUSION

Plastic flow behavior of AISI 204 Cu is rather similar to that of AISI 304 stainless steel. But, the flow stress increases with decreasing Ni content and increasing nitrogen level. The ductility shows low value with decreasing Ni content and increasing nitrogen level. AISI 204 Cu is metastable and undergoes strain-induced martensitic transformation. X-ray

diffraction and electron microscopic studies establish the presence of the transformation products. (The metastability of AISI 304 is already been established in earlier works [2].)

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